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Dielectronic recombination in highly charged He-like ions

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Abstract

We have determined resonant strengths of the KL*n* ($2 \leqslant n \leqslant 5$) resonances for helium-like Ti ions and ($3 \leqslant n \leqslant 5$) resonances for helium-like Fe ions. The results were obtained using the Tokyo electron beam ion trap. Characteristic X-rays from both dielectronic recombination and radiative recombination were detected as the electron beam energy was scanned through the resonances.

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1. Introduction

In the dielectronic recombination (DR) process with a free electron on an ionic target, the incident electron is captured to an excited level while energy is conserved by the promotion of a bound electron. This doubly excited state can decay by autoionization resulting in resonant scattering (RS). Alternatively if the excited state decays by the emission of a photon the process is called DR. This can be summarized with the following equations:

$$\begin{aligned} A_{\mathrm{i}}^{q+} + \mathrm{e}^- \rightarrow A_{\mathrm{d}}^{(q-1)+} &\rightarrow A_{\mathrm{i}}^{q+} + \mathrm{e}^- : \mathrm{RS} \\ &\rightarrow A_{\mathrm{f}}^{(q-1)+} + hv : \mathrm{DR} \end{aligned} \qquad (1)$$

where A_{i}, A_{d} and A_{f} denote the initial, doubly excited and final states, respectively. DR events are named in an inverse Auger notation, KLM therefore corresponds to the bound electron excited from the K shell to the L shell (or M shell), while the free electron is captured to the M shell (or L shell).

Recombination may also occur via a non-resonant process whereby the free electron is captured to a vacant orbital with the emission of a photon. This process is called radiative recombination (RR) and it is essentially the reverse of photoionization.

DR is important in high temperature plasmas, having a large influence on the charge balance.

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Accurate DR cross sections are therefore essential for developing models of these plasmas. DR cross sections and resonant strengths for He-like ions have been measured before in several experiments including merged beams [1], ions yields from an electron beam ion source [2] or electron beam ion trap (EBIT) [3] and from X-rays observed from EBITs [4–6]. Our experiments are in this last category with the X-rays from DR and RR processes inside the trap being measured as the interaction energy is varied. For Fe ions the results [7] were obtained by normalization the KLL resonance strength measured previously [8]. For Ti ions resonance strengths were determined by normalization to the RR count rate [9].

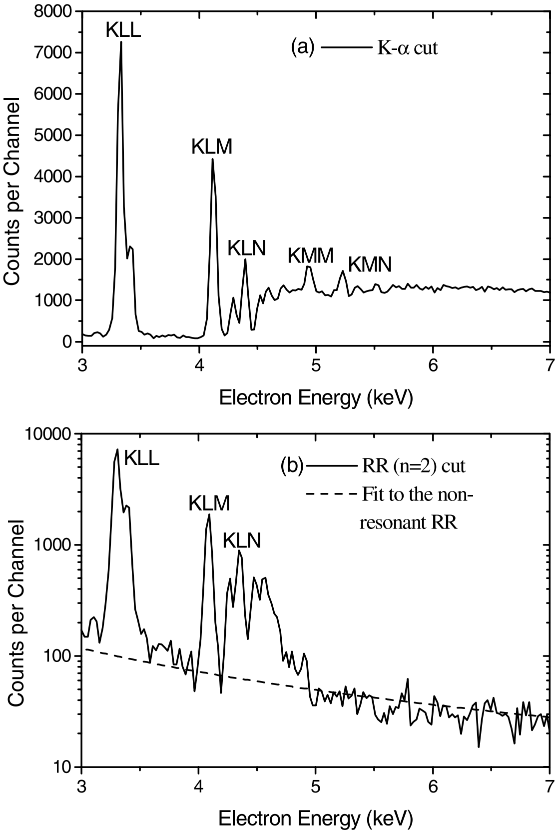

Fig. 1. (a) The K-α cut. This cut includes X-rays from transitions from $n = 2$ to $n = 1$ in the Li-like ion. Below the resonant excitation continuum (≈4.5 keV) several DR resonances can be seen. (b) The RR cut. This cut is taken along the RR into $n = 2$ line. At low energy (<5 keV) a series of DR resonances are observed, superimposed on the RR signal. A fit to the RR signal is also shown.

2. Experimental method

The experiments were all performed using the Tokyo EBIT [10]. Low charge state ions were injected into the trap from a metal vapor vacuum arc (MEVVA) source. Ions are rapidly ionised by successive electron impact ionization events with the electron beam. A predominantly He-like charge balance is soon achieved. The electron beam energy is then rapidly decreased and increased, the interaction energy being swept down and up through the resonances in a saw-tooth pattern. X-rays from DR and RR processes are detected simultaneously at 90° using a Ge solid state detector. A multiparameter system [11] records the X-ray energy and the time during each sweep (which effectively gives the electron beam energy). The energy sweep is fast enough (1–4 ms) to preserve the charge state balance. The sweep is repeated many times before the trap is emptied and the MEVVA retriggered.

3. Results and discussion

The data can be reduced to a 2-d histogram with X-ray energy on one axis and electron energy on the other. From this data-set we can extract cuts along two directions. These cuts are shown for He-like titanium ions in Fig. 1. The K-α cut, Fig. 1(a), consists of X-rays due to decay from $n = 2$ to $n = 1$. At electron energies below the resonant excitation continuum a series of DR resonances can be seen. The second cut is taken along the RR into $n = 2$ line and is shown in Fig. 1(b). X-rays from outer decay of doubly excited states are observed at the same energy as X-rays from RR events. Therefore the DR resonances are superimposed on a smoothly varying RR signal. A fit to this RR signal is also shown and by normalizing the X-ray counts in the DR resonances to the RR counts using theoretical RR cross sections the DR resonant strengths can be found [4–6]. It should be noted that in this experiment the energy was increased above the He-like ionization threshold so that a small fraction of H-like and bare ions were present in the trap. The RR into $n = 1$ signal can then be used to provide a more accurate electron energy scale calibration. This will be discussed fully in a future publication [9].

The resonance strength is normally used when discussing DR because the width of each individual resonance is narrow. The resonant strength, $S^{\mathrm{KL}j}$, is defined as

$$S^{\mathrm{KL}j} = \sum_{\mathrm{d}} \sum_{\mathrm{f}} \int_0^{\infty} \sigma_{\mathrm{idf}}^{\mathrm{DR}}(E)\,\mathrm{d}E, \tag{2}$$

where the initial state, i, is the ground state and the summation is over all doubly excited, d, and final states, f, which contribute to the KLj manifold. The resonance strength can be determined using the relation

$$S^{\mathrm{KL}j} = \frac{I_{\mathrm{tot}}^{\mathrm{KL}j}}{I_{\mathrm{tot}}^{\mathrm{RR}}} \sigma^{\mathrm{RR}} \Delta E \frac{3 - P^{\mathrm{KL}j}}{3 - P^{\mathrm{RR}}}, \tag{3}$$

where $I_{\mathrm{tot}}^{\mathrm{KL}j}$ and $I_{\mathrm{tot}}^{\mathrm{RR}}$ are the total X-ray counts in an energy window of width ΔE, and $P^{\mathrm{KL}j}$ and P^{RR} are the polarizations of the DR and RR photons, respectively.

By defining the expressions for the radiative transition rate $A^{\mathrm{r}}(Z)$, the autoionization rate $A^{\mathrm{a}}(Z)$ and the resonance energy $E(Z)$ in terms of their Z dependence, a scaling law for the resonant strengths was found [7].

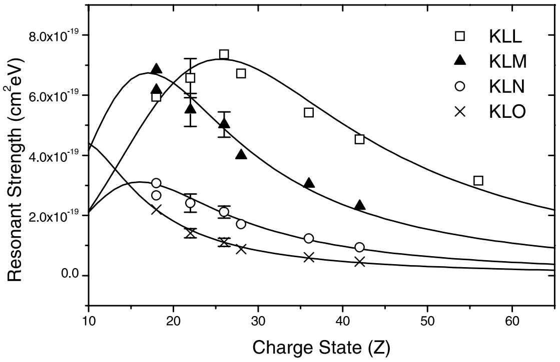

Fig. 2. A comparison of the total DR resonant strengths for He-like ions with the scaling formula from Eq. (4). The data with error bars are ours [7,9], the other data plotted are Ni^{26+}, Mo^{40+} and Ba^{54+} [4], Kr^{34+} [5], Ar^{16+} [6,12] and Fe^{24+} KLL [8].

$$S^{\mathrm{KL}j} = \sum_{\mathrm{d}} \sum_{\mathrm{f}} \frac{\pi^2}{E_{\mathrm{di}}} \frac{g}{2g_{\mathrm{i}}} \frac{A_{\mathrm{di}}^{\mathrm{a}} A_{\mathrm{df}}^{\mathrm{r}}}{\sum A^{\mathrm{a}} + \sum A^{\mathrm{r}}} = \frac{1}{m_1 Z^2 + m_2 Z^{-2}}, \tag{4}$$

with m_1 and m_2 determined from fits to the previous measurements. Fig. 2 shows the results of this scaling law plotted against experimental measurements. Our measurements for iron and titanium are shown with error bars. It is clear that this scaling law provides a good fit to the experimental data. Further benchmark measurements are however needed to test this formula over a wide range of atomic numbers.

4. Conclusions

We have studied the DR process in two species of He-like ions, Fe^{24+} and Ti^{20+}. X-rays from DR and RR of ions trapped in the Tokyo EBIT were detected and used to determine the resonance strengths. Our results compare well with previous measurements.

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